A dosimeter and a dose algorithm have been developed that can isolate the responses due to beta, photon, and neutron radiations.

The LANL Model 8823 Whole-Body TLD and Associated Dose Algorithm

*Jeffrey M. Hoffman and Michael W. Mallett**

Abstract: *The Los Alamos National Laboratory Model 8823 whole-body TLD has been designed to perform accurate dose estimates for beta, photon, and neutron radiations that are encountered in pure calibration, mixed calibration, and typical field radiation conditions. The radiation energies and field types for which the Model 8823 dosimeter is capable of measuring are described. The Model 8823 dosimeter has been accredited for all performance testing categories in the Department of Energy Laboratory Accreditation Program for external dosimetry systems. The philosophy used in the design of the Model 8823 dosimeter and the associated dose algorithm is to isolate the responses due to beta, photon, and neutron radiations; obtain radiation quality information; and make functional adjustments to the elemental readings to estimate the dose equivalent at 7, 300, and 1,000 mg cm^{-2}, representing the required reporting quantities for shallow, lens-of-the-eye, and deep dose, respectively.*

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Key words: *calibration; dose; dosimetry; radiation dose*

Los Alamos National Laboratory (LANL) is a large multi-disciplined research institution that utilizes a wide variety of radioisotopic sources, radiation producing machines, and critical assemblies. Employees may receive occupational radiation exposure from beta, photon, and/or neutron radiations, each present at LANL with a wide spectrum of energies. Most occupational external radiation exposure at LANL is due to neutron radiation which accounts for about 60% of the collective external effective dose equivalent. Neutron radiation exposures at LANL originate from isotopic sources, nuclear materials handling, critical assemblies, and accelerators. Although a lesser part of the total, beta and photon radiation exposures occur from a larger variety of source-types. In addition to those stated for neutron radiations, these sources include radiation producing machines, medical isotopes for research and therapy, and others.

The physical features of the Model 8823 dosimeter and the associated computational dose algorithm have been designed to report dose equivalent at the tissue depths of 7, 300, and 1,000 mg cm^{-2}, which correspond to shallow, lens-of-the-eye, and deep dose, respectively. The design of the dosimeter and algorithm are such that the responses due to beta, photon, and neutron radiations are isolated; a measure of the effective energy, radiation quality, or the degree-of-moderation (depending on radiation type) is obtained; and a functional correction to the elemental responses are made to derive the doses at the specified depths of interest. This methodology allows for excellent pure field as well as mixed field measurement performance and meets the requirements specified in 10CFR835 (1998) "Occupational Radiation Protection" and other DOE requirements. The Model 8823 dosimeter was accredited by Department of Energy Laboratory Accreditation Program (DOELAP) for all performance test categories in the spring of 1997.

DOSIMETER DESCRIPTION

The Model 8823 thermoluminescent dosimeter is a custom LANL design that contains two Harshaw/Bicron-NE TLD cards.† Fig. 1 shows the components of the Model 8823 TLD cardholder. The Model 8823 cardholder is

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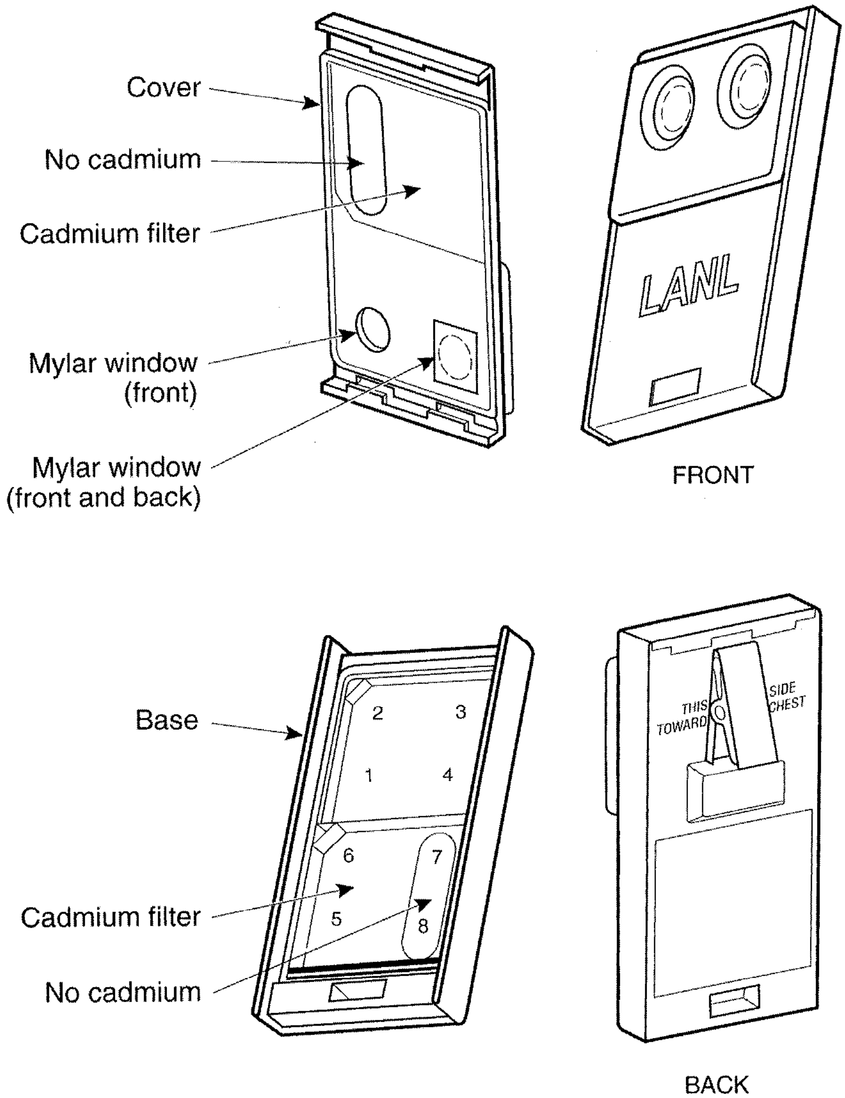

Figure 1. LANL Model 8823 TLD cardholder.

Table 1. LANL model 8823 dosimeter configuration.

Pos.	TLD Type	Filter, Front	Filter, Rear
		Beta-Gamma (7774 TLD Card)	
1	700	ABS, 0.704 cm (600 mg cm^{-2})	ABS, 0.178 cm (185 mg cm^{-2})
2	700	Mylar, 0.004 cm (5 mg cm^{-2})	ABS, 0.178 cm (185 mg cm^{-2})
3	700	Mylar, 0.008 cm (10 mg cm^{-2})	ABS, 0.178 cm (185 mg cm^{-2})
4	400	ABS, 0.704 cm (600 mg cm^{-2})	ABS, 0.178 cm (185 mg cm^{-2})
		Neutron (6776 TLD Card)	
Pos.	TLD Type	Filter, Front	Filter, Rear
5	600	ABS, 0.178 cm (185 mg cm^{-2})	ABS, 0.178 cm (185 mg cm^{-2}) Cd, 0.053 cm (461 mg cm^{-2})
6	700	ABS, 0.178 cm (185 mg cm^{-2})	ABS, 0.178 cm (185 mg cm^{-2}) Cd, 0.053 cm (461 mg cm^{-2})
7	700	ABS, 0.178 cm (185 mg cm^{-2}) Cd, 0.053 cm (461 mg cm^{-2})	ABS, 0.178 cm (185 mg cm^{-2})
8	600	ABS, 0.178 cm (185 mg cm^{-2}) Cd, 0.053 cm (461 mg cm^{-2})	ABS, 0.178 cm (185 mg cm^{-2})

made of black-colored ABS plastic to minimize light-induced signal on the TLD elements. The holder features a rubber gasket around the seat for the two TLD cards to prevent dirt and foreign substances from contaminating the TL elements. The holder also contains a 0.53-mm-thick cadmium box into which the neutron TLD card is placed. The cadmium box has an open window under positions 7 and 8 (next to the body of the wearer) and over positions 5 and 6 (towards the incident radiation) to facilitate the combined Albedo and Anti-Albedo design described below. The holder provides 600 mg cm^{-2} ABS plastic filtration over positions 1 and 4 for determining photon deep dose. Positions 2 and 3 are beta windows that are covered with a single and double layer of aluminized Mylar, respectively.‡ The aluminized Mylar is coated with a black paint on the back to minimize light infiltration.

The holder is labeled with instructions to personnel to wear the holder with the backside toward the chest and to not cover the Mylar windows. The built-in clip is fixed on the back of the holder and situated so that if the user wears the dosimeter on a lanyard, the beta windows will be raised above the other identification cards typically worn by LANL personnel. The LANL postal address is included on the holder; in the event the dosimeter is removed from the Laboratory, it can be mailed postage-guaranteed back to the Personnel Dosimetry Operations Team.

Table 1 shows the TLD element type, location, and filtration of the Model 8823 dosimeter. Each of the two TLD cards contains four TLD elements for a total of eight TLD elements in a fully assembled dosimeter. One card is a Harshaw/Bicron-NE Model 7774 TLD card in which elements one, two, and

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three are TLD-700 material (LiF:Mg, Ti enriched in ^{7}Li) and element four is TLD-400 (CaF_2:Mn). All four elements on this card are mounted bare on Kapton.‡ This card is used for estimating beta and photon doses. Elements one and four are 0.38 mm thick and are heavily filtered with 600 mg cm^{-2} ABS plastic. These elements are used for determining penetrating photon dose, calculating an effective photon energy, and estimating a predicted photon contribution to elements two and three. Elements two and three are 0.15 mm thick and are used primarily for beta dosimetry with only minimal filtration of 5 and 10 mg cm^{-2} (aluminized Mylar), respectively.

The second card is a Harshaw/Bicron-NE Model 6776 TLD card. This card allows for the paired placement of TLD-600 and TLD-700 TLD elements (each 0.38 mm thick) within the Model 8823 TLD cardholder. The Model 6776 TLD card is placed in the cadmium box. Positions seven and eight form a classic Albedo detector with a TLD-600/-700 pair surrounded by cadmium except for an opening toward the body. Positions five and six are an incident thermal neutron detector, also called an Anti-Albedo detector, with the TLD-600/-700 pair surrounded by cadmium except for an opening away from the body. The ratio of the net neutron induced signal on the Anti-Albedo detector to that on the Albedo detector provides a measure of the degree-of-moderation of the neutron field. This measure is used to correct the highly energy-dependent Albedo neutron response to yield an estimate of the neutron dose.

The Model 8823 dosimeter replaced a Model 7776-type TLD dosimeter historically used as the dose-of-record at LANL. The retired dosimeter relied heavily on the use of site-specific neutron correction factors (NCF) for neutron dosimetry. The technique utilized an essentially bare TLD-600 and TLD-700 pair in a quasi-Albedo arrangement (i.e., without a cadmium or other neutron absorbing shield anterior to the TLD elements). The net neutron signal is very highly energy dependent and requires the site-specific NCF to convert the response to dose. NCFs can vary by more than an order of magnitude at LANL facilities. Consequently, in the past, NCFs were assigned at very conservative values such that neutron doses were typically over-estimated by a factor of two to three (Blackstock and Storm 1980; Casson et al. 1995; Harvey et al. 1993; Hoffman et al. 1992; Romero 1997). NCFs are still used with the model 8823 for isolated special cases.

At high neutron energies, the Albedo dosimeter does not provide

Table 2. DOELAP irradiation techniques and effective energies.

Photon		Beta		Neutron
Source	E (keV)	Source	E (MeV)	Source
K17	17	^{204}Tl	0.76	Bare ^{252}Cf
M30	20	$^{90}Sr/Y$	2.27	D_2O moderated ^{252}Cf
S60	36			
K59	59			
^{241}Am	59			
M150	70			
H150	120			
^{137}Cs	662			

Table 3. Guide to Variables in Model 8823 Algorithm.

RCF*x*	= reader correction factor (from reader calibration) for element *x*
ECC*x*	= element correction coefficient (from card calibration) for element *x*
NCR*x*	= net corrected reading of element *x* (RCF, ECC and background correction applied)
R67	= ratio of NCR6 to NCR7
R47	= ratio of NCR4 to NCR7
R41	= ratio of NCR4 to NCR1
SO	= calculated effective photon energy (keV)
E2B	= net beta signal on element 2
E3B	= net beta signal on element 3
E2G	= predicted photon contribution to signal on element 2
E3G	= predicted photon contribution to signal on element 3
E8N	= net neutron signal on element 8
E5N	= net neutron signal on element 5
E23GE1	= predicted photon contribution to signal on elements 2 and 3 as a function of NCR1
R2B3B	= ratio of E2B to E3B
R5N8N	= ratio of E5N to E8N
HSBE2B	= ratio of beta shallow dose equivalent to E2B
HEBE2B	= ratio of beta eye dose equivalent to E2B
HSGE3	= ratio of gamma shallow dose equivalent to NCR3
HSGE1	= ratio of gamma shallow dose equivalent to NCR1
HDGE1E7	= ratio of gamma deep dose equivalent to the average value of NCR1 and NCR7
HEGE1	= ratio of gamma eye dose equivalent to NCR1
HDNE8N	= ratio of neutron deep dose equivalent to E8N
HSB	= beta shallow dose equivalent (mrem)
HEB	= beta eye dose equivalent (mrem)
HSG	= gamma shallow dose equivalent (mrem)
HDG	= gamma deep dose equivalent (mrem)
HEG	= gamma eye dose equivalent (mrem)
HDN	= neutron deep dose equivalent (mrem)
HS	= total shallow dose equivalent (mrem)
HD	= total deep gamma (or photon) dose equivalent (mrem)
HE	= total eye dose equivalent (mrem)
HN	= total deep neutron dose equivalent (mrem)

an accurate measure of neutron dose due to its energy dependence. For this reason, the supplemental LANL track-etch dosimeter (TED), which provides a better quality measurement of high-energy neutron radiation than does the Model 8823, is issued to personnel for select operations.

ALGORITHM DESCRIPTION

The general algorithm technique adopted for the Model 8823 dosimeter is similar to that developed by Stanford and McCurdy (1990). The basis for the algorithm was to determine the elemental responses for each of the eight elements in the Model 8823 dosimeter using a full set of DOELAP style irradiation categories. A minimum of ten dosimeters were irradiated to each of the DOELAP techniques shown in Table 2. These irradiations included photons with an effective energy ranging from 17 keV to 662 keV, betas with maximum energies of 760 keV to 2.27 MeV, and bare and moderated fission neutron sources.

For the purpose of understanding the flow of information referenced in the development and use of the algorithm, the following variables are defined in Table 3. The flowchart for the algorithm is shown in Fig. 2. For algorithm development and for the processing of field dosimeters, net corrected readings are determined for all eight elements in the Model 8823 dosimeter. The net corrected reading has the Reader Correction Factor (RCF), Element Correction Coefficient (ECC), and background correction applied. The net corrected reading for each element, NCRx, is calculated as

$$NCRx = \frac{\text{elemental reading(nC)}x{*}ECCx}{RCFx} - \text{background } x, \quad (1)$$

where the background is calculated as a function of time since the last read date for known deployment conditions (Mallett 1998).

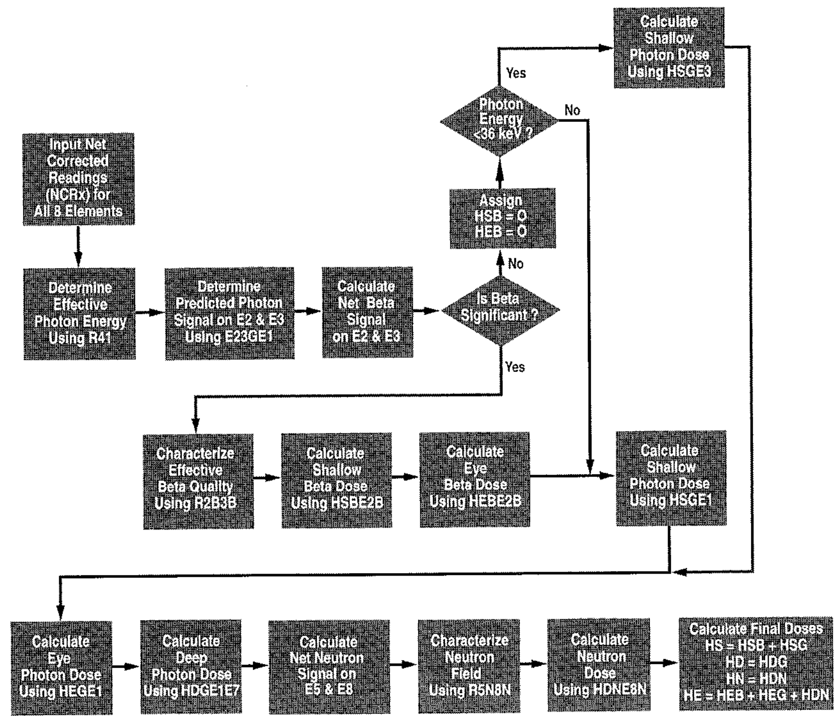

Figure 2. LANL Model 8823 algorithm flowchart.

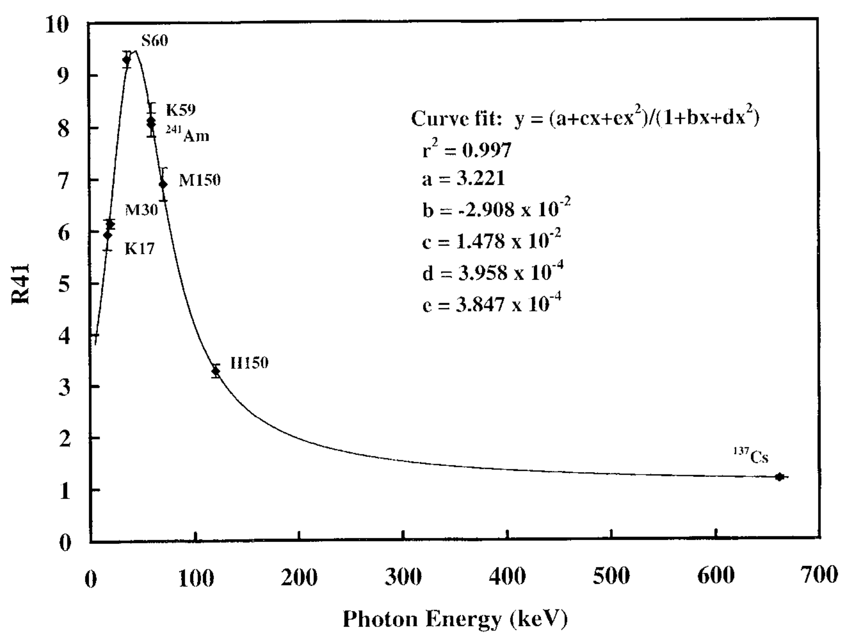

Figure 3. Photon energy discrimination.

Characterize effective photon energy

The effective photon energy, SO, is determined using R41 as shown in Fig. 3. At relatively high photon energies, calcium fluoride and lithium fluoride phosphors respond identically. However, as the photon energy decreases, the calcium fluoride phosphor (element 4) over-responds relative the lithium fluoride phosphor (element 1). Thus, R41 yields a measure of the effective photon energy.

A maximum overresponse in calcium fluoride is reached at about 36 keV for the Model 8823 design. Below this energy, ambiguous effective photon energy results are obtained when solely based upon R41. However, below 36 keV, SO is identified correctly via large values of R47 (>50) and R67 (>5). Photon energies above ^{137}Cs are treated as 662 keV.

Characterize beta response and determine shallow and lens-of-eye beta dose equivalents

The beta signal present on NCR2 and NCR3 is isolated by subtracting the predicted photon contribution to these elements using NCR1 and SO, as shown in Fig. 4. The resulting value for E23GE1 is multiplied by NCR1 to yield the predicted photon contributions to NCR2 and NCR3, as given by

$$\mathrm{E2G} = \mathrm{E23GE1} \times \mathrm{NCR1}, \quad (2)$$

and

$$\mathrm{E3G} = \mathrm{E2G}. \quad (3)$$

The net beta signals for NCR2 and NCR3 are subsequently calculated as given by

$$\mathrm{E2B} = \mathrm{NCR2} - \mathrm{E2G}, \quad (4)$$

and

$$\mathrm{E3B} = \mathrm{NCR3} - \mathrm{E3G}. \quad (5)$$

Significant beta radiation is identified for the conditions E3B $\geq$ 25 (photon-equivalent residual beta signal) and E2B $\geq$ 0.10 $\times$ E2G.

If the beta radiation signal is determined to be significant, the value for R2B3B is used as a measure of the beta radiation quality. For the Model 8823, R2B3B ~ 1.3 for pure ^{204}Tl, and R2B3B ~ 1.0 for pure $^{90}Sr/Y$ fields. The shallow and lens-of-the-eye beta dose equivalents are then calculated as a function of E2B modified by the correction factors, HSBE2B and HEBE2B, respectively, both determined by R2B3B.

Determine shallow photon dose equivalent

If beta radiation was determined to be present, or the photon energy is greater than or equal to 36 keV, the shallow photon dose is calculated using NCR1. The effective photon energy determines the correction factor, HSGE1, used to calculate the shallow photon dose equivalent.

If no beta radiation was determined to be present and SO is less than 36 keV, the shallow photon dose is calculated using NCR3. The effective photon energy determines the correction factor, HSGE3, used to calculate the shallow photon dose equivalent.

Determine lens-of-eye photon dose equivalent

For all cases, the lens-of-the-eye photon dose equivalent is calculated using NCR1. The effective photon energy determines the correction factor, HEGE1, used to calculate the lens-of-the-eye photon dose equivalent.

Determine deep photon dose equivalent

The deep photon dose equivalent is then calculated using the average of NCR1 and NCR7. The effective photon energy determines the correction factor, HDGE1E7, used to calculate the deep photon dose equivalent. For the Model 8823, two separate functions are required for the determination of HDGE1E7, as shown in Fig. 5.

Characterize neutron response and determine neutron dose equivalent

The net neutron signals on NCR5 and NCR8 are determined according to

$$\mathrm{E5N} = \mathrm{NCR5} - \mathrm{NCR6}, \quad (6)$$

and

$$\mathrm{E8N} = \mathrm{NCR8} - \mathrm{NCR7}. \quad (7)$$

Significant neutron signal is identified for the conditions E8N $\geq$ 10 and E5N $\geq$ 3 (photon-equivalent residual neutron signal), and NCR8/NCR7 $\geq$ 1.18 (i.e., neutron-plus-photon signal at least 18% higher than photon-only signal). If the neutron radiation signal is determined to be significant, the degree-of-moderation of the neutron field is determined by R5N8N. The neutron dose equivalent is calculated as a function of E8N modified by the correction factor, HDNE8N.

The degree-of-moderation function shown in Fig. 6 is based upon irradiations performed at the LANL

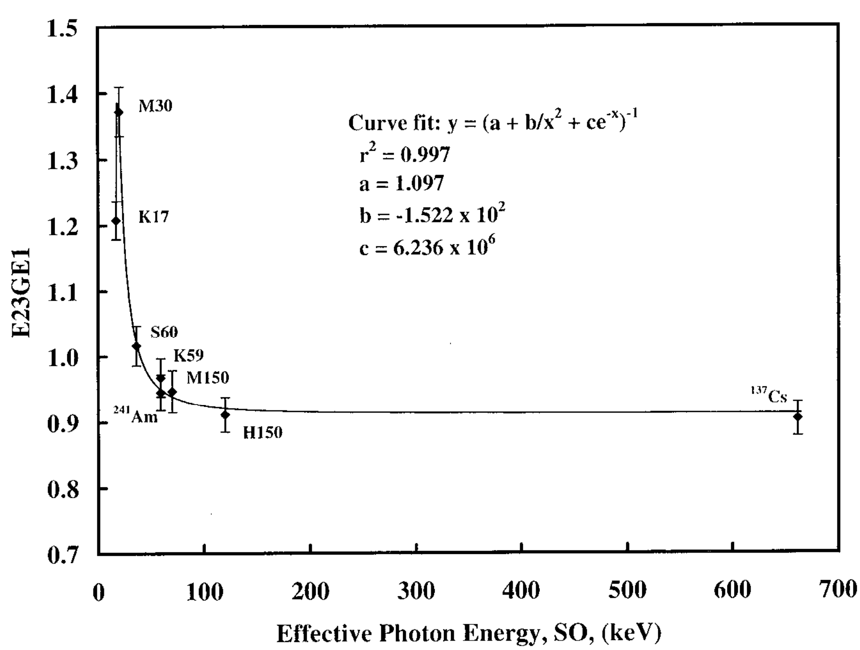

Figure 4. Predicted photon contribution to total signal on NCR2 and NCR3 with respect to NCR1.

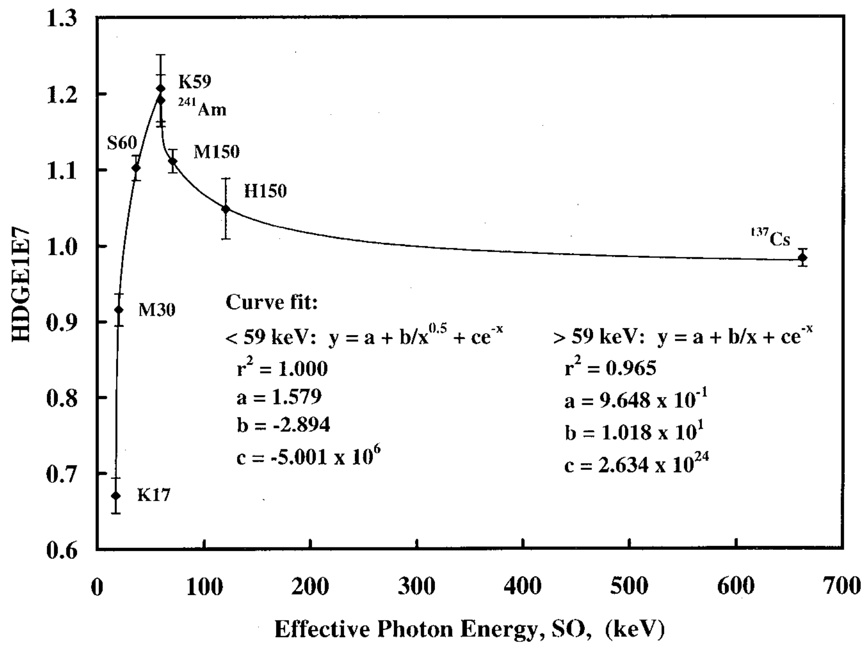

Figure 5. Deep photon dose equivalent calculation using the average of NCR1 and NCR7 with respect to SO.

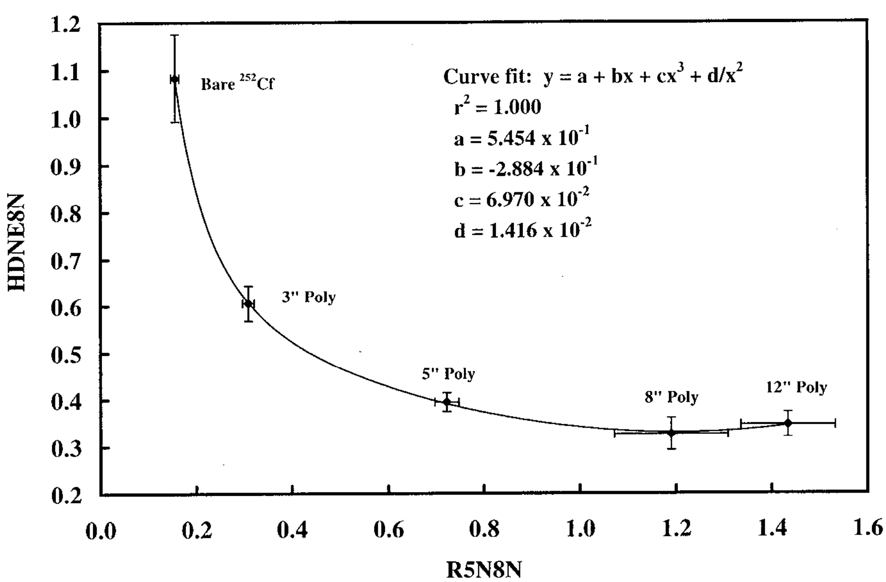

Figure 6. Neutron dose equivalent calculation using the degree-of-moderation indicated by R5N8N with respect to E8N.

Low-Scatter Calibration Facility using a NIST traceable ^{252}Cf source. The source was placed at the center of polyethylene spheres ranging in diameter from 3 inches to 12 inches, to obtain increasingly moderated neutron spectra.

Assign total shallow, deep, neutron and lens-of-eye dose equivalents

The total shallow, deep, neutron, and lens-of-the-eye doses are assigned according to the following:

Total shallow dose equivalent:

$$HS = HSB + HSG \qquad (8)$$

Total deep photon dose equivalent:

$$HD = HDG \qquad (9)$$

Total neutron dose equivalent:

$$HN = HDN \qquad (10)$$

Total lens-of-eye dose equivalent:

$$HE = HEB + HEG + HDN \qquad (11)$$

INHERENT ALGORITHM PERFORMANCE

The inherent performance of the Model 8823 dose algorithm in DOELAP pure and mixed radiation fields was analyzed using the original DOELAP development data. The irradiation data was used to produce an average expected NCR per unit delivered dose for each of the eight TL elements for each type of radiation. This information was input into the final algorithm to simulate pure and mixed radiation fields to analyze any inherent algorithm bias. This analysis represents best-case scenarios for the algorithm assuming the reader and TLDs are properly calibrated in the same fashion as when the algorithm data was initially generated. It also assumes no other systematic errors are present.

Table 4 shows the predicted percent shallow and deep biases for the calculated results when the average dosimeter readings are input into the algorithm for each of the pure DOELAP field categories as shown. The mixture assessment was performed using two DOELAP fields (x and y) in proportions of 1x:3y, 1x:2y, 1x:1y, 2x:3y, 2x:1y, 3x:2y, and 3x:1y, which includes the entire range of proportions that may be delivered in DOELAP mixture testing. The specific results of the mixture analysis are not given in this report.

The inherent algorithm performance is well within the prescribed DOELAP performance criterion for pure fields and the DOELAP tested mixtures. The inherent algorithm performance for mixtures not tested by DOELAP are also well within DOELAP performance criterion with the exception of some mixtures involving K17. Since C_x factors for K17 are currently in revision, it is expected that improved

Table 4. Pure field inherent algorithm performance

Pure field	% Shallow bias	% Deep bias
K17[a]	−8.2	−12.8
M30	−3.0	2.1
S60	2.1	0.2
^{241}Am	−1.5	1.0
M150	2.8	−0.1
H150	0.4	0.2
^{137}Cs	0.0	−0.5
^{204}Tl	0.2	NA
^{90}Sr	−3.4	NA
Bare ^{252}Cf[b]	NA	NA
Moderated ^{252}Cf[b]	NA	NA

[a] Denotes effective energy calculation was temporarily allowed to go to less than 20 keV.
[b] Neutron Categories have no inherent algorithm bias because the computational result is based solely on the DOELAP Neutron Correction Factors for bare and moderated sources.

performance will be realized once the new factors are incorporated.

The favorable inherent algorithm performance is not limited to mixtures involving two fields but extends to mixtures involving three or more radiation fields which are not tested by DOELAP. The superior mixed field performance of the Model 8823 dosimeter is a result of its ability to separate the contributions from beta, photon, and neutron radiations and adjust the readings to account for physical limitations to provide a reasonable estimate of dose.

ADDITIONAL RELATED INFORMATION

The LANL Model 8823 dosimeter has been accredited by DOELAP for all applicable DOELAP categories (no exceptions are required). The general beta category (VA), which includes both ^{90}Sr/^{90}Y and ^{204}Tl, is selected over the special contact geometry uranium category (VB) and special beta category (VC), which utilizes only ^{90}Sr/^{90}Y or ^{204}Tl. The algorithm described above is used for field doses and all DOELAP categories except neutron, for which special calibration factors are applied for the moderated and/or bare ^{252}Cf DOELAP fields. This is consistent with the guidelines of the DOELAP performance testing program.

For personnel working near high-energy neutron radiation sources (e.g., the Los Alamos Neutron Science Center, LANSCE), the LANL Track-Etch Dosimeter (TED) is issued as a supplement to the Model 8823.

The LANL TED, shown in Fig. 7, contains three dosimetry-grade CR-39 track-etch plastic foils.† The foils are placed in a hemispherically-shaped ABS plastic case. Inside the case is a triangular polystyrene pyramid with sides inclined at 40° to the base. Each foil is placed on a face of the pyramid and the domed cap is placed over this arrangement. The purpose of the pyramidal arrangement is to minimize angular dependency. The overall diameter is 58 mm and the overall height is 20 mm. The LANL TED passed DOELAP bare and moderated ^{252}Cf performance test categories in the fall of 1998.

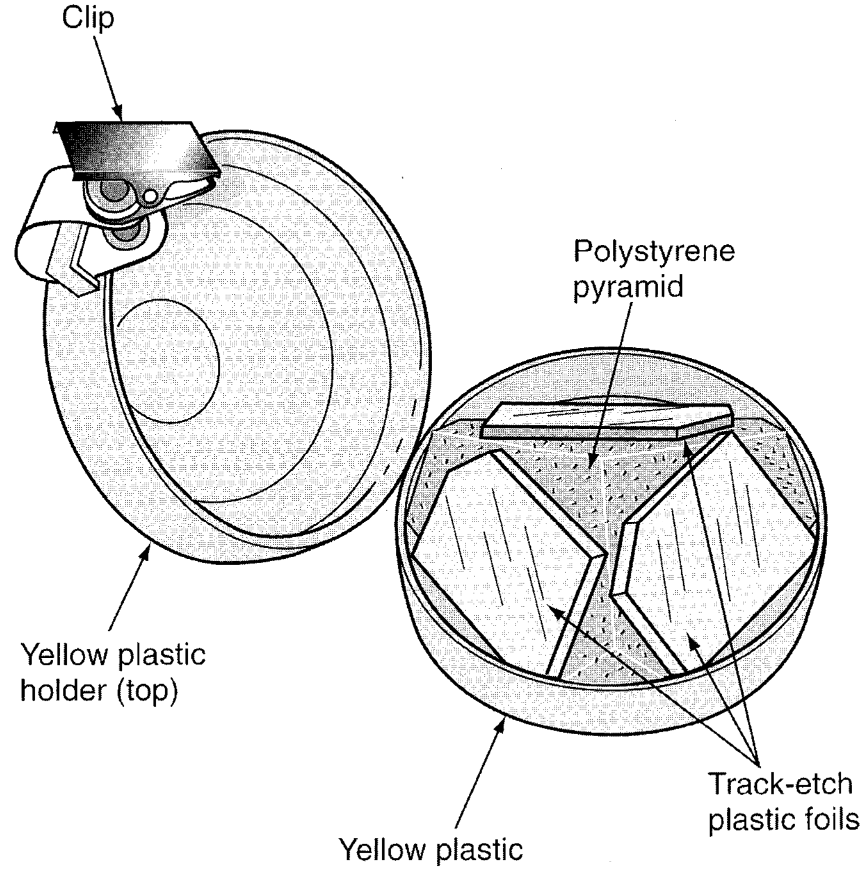

Figure 7. LANL track-etch dosimeter.

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